SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release Distribution Unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 95-0280
6a. NAME OF PERFORMING ORGANIZATION University of Notre Dame Electrical Engineering Dept. / 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION AFOSR
6c. ADDRESS (City, State and ZIP Code) Notre Dame, IN 46556	7b. ADDRESS (City, State and ZIP Code) SCUMO CO 8C
8a. NAME OF FUNDING/SPONSORING ORGANIZATION U.S. Air Force Office of Scientific Research / 8b. OFFICE SYMBOL (If applicable) NE	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER afosr 91-0211
8c. ADDRESS (City, State and ZIP Code) Bolling Air Force Base Washington, D.C. 20332-6448	10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO. 61102F; PROJECT NO. 2306; TASK NO. B1; WORK UNIT NO.
11. TITLE (Include Security Classification) Quantum Transport	
12. PERSONAL AUTHOR(S) Lent, Craig S.; Porod, Wolfgang; Bernstein, Gary; Bandyopadhyay, Suprivo	

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Final	FROM 91-3-15 TO 94-8-14	94-8-15	28

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

During the period March 15, 1991 to August 14, 1994, research carried out by the Nanostructures Group in the Department of Electrical Engineering at Notre Dame was concerned with a variety of quantum transport in mesoscopic structures. This research was funded by the Air Force Office of Scientific Research under Grant No. AFOSR-91-0211. The major issues examined included quantum transport in high magnetic fields and modulated channels, Coulomb-coupled quantum dot systems, transmission resonances and zeroes in resonant transport, self-consistent Hartree calculations of transport, lateral quantum wires an *pn*-junction formation, quantum magnetotransport in disordered systems, magnetoelectric states in quantum wires, anomalous magnetoresistance, electromigration, collision retardation and phonon effects in hot-electron transport, spin-polarized single electronics, single-particle lifetimes in quasi-1D structures, quantum transport experiments in metals, the mesoscopic photovoltaic effect, and new techniques for fabricating quantum structures in semiconductors.

DTIC QUALITY INSPECTED 5

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL ~~Ha~~ Lt Col Pomrenke	22b. TELEPHONE NUMBER (Include Area Code) 202 767-4931	22c. OFFICE SYMBOL NE

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE. SECURITY CLASSIFICATION OF THIS PAGE

Final Report on Grant AFOSR-91-0211

Quantum Transport

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DTIC TAB	☐	
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Dist	Avail and / or Special	
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15 August, 1994

Final Report for Period 15 March 1991 — 14 August 1994

Prepared for
U. S. Air Force Office of Scientific Research
Bolling Air Force Base
Washington DC 20332-6448

Table of Contents

I. Introduction

During the period March 15, 1991 to August 14, 1943, research carried out by the Nanostructures Group in the Department of Electrical Engineering at Notre Dame was concerned with a variety of quantum transport in mesoscopic structures. This research was funded by the Air Force Office of Scientific Research under Grant No. AFOSR-91-0211. The major issues examined included quantum transport in high magnetic fields and modulated channels, Coulomb-coupled quantum dot systems, transmission resonances and zeroes in resonant transport, self-consistent Hartree calculations of transport, lateral quantum wires an *pn*-junction formation, quantum magnetotransport in disordered systems, magnetoelectric states in quantum wires, anomalous magnetoresistance, electromigration, collision retardation and phonon effects in hot-electron transport, spin-polarized single electronics, single-particle lifetimes in quasi-1D structures, quantum transport experiments in metals, the mesoscopic photovoltaic effect, and new techniques for fabricating quantum structures in semiconductors.

The research supported by this grant resulted in 44 journal papers, 42 conference presentations, and 12 research seminars. The research contributed to the granting of 8 M.S. degrees, and 3 Ph.D. degrees.

II. Research Description

Quantum Transport in Magnetic Fields

Investigators: Craig S. Lent

We have been investigating ballistic electron transport in quantum channels with an applied magnetic field. The magnetic field is in the direction perpendicular to the plane of the two-dimensional electron gas from which the channels are formed. Electrons in such geometries form magnetic edge states, which carry current, and circulating Landau levels which do not. We solve the Schrödinger equation with the magnetic field included through a vector potential. The precise eigenstates of the system, and the current density distribution can be calculated. We have extended the Quantum Transmitting Boundary Method, an adaptation of the Finite Element Method for current-carrying quantum states, to include the effect of the applied magnetic field.

We have examined electron states in a circular quantum dot, establishing a rigorous connection between actual wavefunctions and semiclassical "skipping orbits". We have also used this technique to examine transport in quantum channels with a periodic modulation in the channel width. This investigation yielded two surprising results: 1) that, in the high-field regime, the electron in an infinite modulated channel propagates as though it were completely free, but with a *renormalized effective mass*, and 2) that the quantization of conductance characteristic of short ballistic constrictions is recovered for longer (but finite) periodically-modulated channels. This latter effect has lead us to make new predictions concerning the quenching of integer quantum Hall effect plateaus in such structures.

Resulting Publications and Presentations:

Craig S. Lent, "Edge States in a Circular Quantum Dot", *Phys. Rev. B* **43**, 4179 (1991).

Craig S. Lent and Manhua Leng, "Bloch states of electrons in a corrugated quantum channel", *Applied Physics Letters* **58**, 1650 (1991).

Craig S. Lent and Manhua Leng, "Magnetic edge states in a corrugated quantum channel," *Journal of Applied Physics* **70**, 3157 (1991).

Manhua Leng and Craig S. Lent, "Magnetic Edge States in a Quantum Channel with a Periodic Array of Antidots," *Superlattices and Microstructures* **11**, 351 (1992).

Manhua Leng and Craig S. Lent, "Recovery of quantized ballistic conductance in a periodically modulated channel," *Physical Review Letters* **71**, 137 (1993).

Manhua Leng and Craig S. Lent, "The Quantum Transmitting Boundary Method in an Applied Magnetic Field," to appear in *Journal of Applied Physics*.

Manhua Leng and Craig S. Lent Recovery of quantized ballistic conductance in a periodically modulated channel, submitted to P*hysical Review* B.

"Magnetic Edge States in a Quantum Channel with a Periodic Array of Antidots," Manhua Leng and Craig S. Lent, *International Symposium on Nanostructures and Mesoscopic Systems*, Santa Fe, NM, May 1991.

"Magnetotransport Through Electron Waveguides with a Few Elastic Scatterers," Manhua Leng and Craig S. Lent, *American Physical Society March Meeting*, Indianapolis, IN, 1992.

"Calculation of Ballistic Transport in a Magnetic Field: Recovery of Conductance Quantization," Manhua Leng and Craig S. Lent, *International Workshop on Computational Electronics*, Leeds, UK, August, 1993.

"Non-monotonic conductance quantization in a periodically modulated channel," Manhua Leng and Craig S. Lent, *American Physical Society March Meeting*, Pittsburgh, PA, 1994.

"Magnetic Quasi-Bound State and Resonant Coupling of Edge States," Manhua Leng and Craig S. Lent, presented at the *3rd International Workshop on Computational Electronics*, Portland, OR, May 1994.

Coulomb-coupled Quantum Dot Systems

Investigators: Craig S. Lent, Wolfgang Porod, and Gary H. Bernstein

As an outgrowth of our investigations of the effects of Coulomb-exclusion effects, we considered the behavior of cells composed of coupled quantum dots. Each cell is occupied by two electrons. Tunneling between dots in the same cell is possible, but not between cells. Thus, rather than seeing Bloch behavior, correlated quantum states of the cells are formed. Information and energy, but not charge, can be transported along a linear array of such cells. This research led to considerations of the possibilities of using non-uniform arrays of such cells as computing elements. Designs for implementing computational functions as complex as full adders have been simulated. This program, focussed on producing actual devices, has transitioned into a separately supported research effort under the ARPA ULTRA program to develop ultrafast, ultradense computing components. *This is an example of a transition from basic research into applied device-oriented research.*

The underlying formalism we have developed involves expressing the electron-electron interaction in the form of a second-quantized Hamiltonian, and solving the resulting Schrödinger equation directly in the basis of many-electron states. This approach, which is numerically tractable for few-electron problems, is one we hope to generalize to related transport problems. It seems ideal for attacking certain problems in the quantum theory of dissipation.

Resulting Publications and Presentations:

Craig S. Lent, "A Simple Model of Coulomb Effects in Semiconductor Nanostructures," in *Nanostructures and Mesoscopic Systems*, edited by Wiley P. Kirk and Mark A. Reed, 183 (Academic Press, Boston, 1992).

Craig S. Lent, P. Douglas Tougaw, and Wolfgang Porod, "Bistable Saturation in Coupled Quantum Dots for Quantum Cellular Automata," *Appl. Phys. Lett.*, **62**, 714 (1993).

Craig S. Lent, P. Douglas Tougaw, Wolfgang Porod and Gary H. Bernstein, "Quantum Cellular Automata," to appear in *Nanotechnology* **4**, (1993).

Craig S. Lent and P. Douglas Tougaw, "Lines of interacting quantum-dot cells: a binary wire," *Journal of Applied Physics*, **74**, 6227 (1993).

Craig S. Lent, P. Douglas Tougaw, and Wolfgang Porod, "Bistable saturation in coupled quantum-dot cells", *Journal of Applied Physics* **74**, 3558 (1993).

Craig S. Lent and P. Douglas Tougaw, "Bistable saturation due to single electron charging in rings of tunnel junctions," *Journal of Applied Physics* **75**, 4077-4080 (1994).

P. Douglas Tougaw and Craig S. Lent, "Logical devices implemented using quantum cellular automata," *Journal of Applied Physics* 75, 1818-1825 (1994).

C. S. Lent, P. Douglas Tougaw, and Wolfgang Porod, "A Bistable Quantum Cell for Cellular Automata," *Proceedings of the International Workshop on Computational Electronics*, University of Illinois at Urbana-Champaign, May 1992.

C.S. Lent, "Quantum Cellular Automata," seminar at the Department of Electrical Engineering, University of Illinois at Urbana, October 6, 1992.

C. S. Lent, P. D. Tougaw, W. Porod, and G. H. Bernstein, "Quantum Cellular Automata," presented at the *International Symposium on New Phenomena in Mesoscopic Structures*, in Hawaii, December, 1992.

W. Porod, "Dissipation in Computation," seminar at the School of Electrical Engineering, Purdue University, October 1992.

Craig S. Lent, P. Douglas Tougaw, Wolfgang Porod, and Gary Bernstein," Quantum Cellular Automata," presented at the *International Workshop on Quantum Structures*, Santa Barbara, California, March 1993.

C.S. Lent, "Quantum Cellular Automata," seminar at the Department of Electrical Engineering, Purdue University, April 14, 1993.

Craig S. Lent, "Quantum Cellular Automata," seminar presented at Wright Laboratories, Wright-Patterson AFB, Dayton OH, Sept. 1993.

Craig S. Lent, P. Douglas Tougaw, Wolfgang Porod, and Gary H. Bernstein, (Invited), "Quantum Cellular Automata," presented at the *21st Midwest Solid State Theory Symposium*, Detroit, Michigan, October 1993.

Craig S. Lent, Wolfgang Porod, and P. Douglas Tougaw, (Invited), "Quantum Simulation of Several-Particle Systems," presented at the *Microwave Theory and Techniques Symposium*, Workshop on *Combined Self-Consistent Particle Transport Simulation and*

Full Wave Dynamic Field Simulation for Monolithic Solid State Device and Circuit Calculations, Atlanta, Georgia, June 1993.

Craig S. Lent, "Quantum Cellular Automata," seminar presented at the Department of Electrical Engineering, University of Maryland, College Park, MD, October 1993.

Craig S. Lent, "Quantum Dots Coupled in a Cellular Automata Architecture," seminar presented at the Department of Physics and Astronomy, Michigan State University, East Lansing, MI, January 1994.

Craig S. Lent, Wolfgang Porod, and P. Douglas Tougaw, "Quantum Simulation of Several-Particle Systems," in *Proceedings of the International Workshop on Computational Electronics*, C. Snowden and M. Howes, eds., pp. 303 - 307; presented at the *International Workshop on Computational Electronics*, Leeds, England, August 1993.

Craig S. Lent, P. Douglas Tougaw, and Wolfgang Porod, "Quantum Cellular Automata," abstract published in the *Bulletin of the APS*, Vol. 39, No. 1, p. 799, March 1994; presented at the *1994 March Meeting of the American Physical Society*, Pittsburgh, Pennsylvania, March 1994.

Craig Lent and P. Douglas Tougaw, (Invited) "Quantum Cellular Automata," invited talk at the International Conference on Advanced Microelectronic Devices and Processing, Sendai, Japan, March 1994

Craig Lent, "Quantum Cellular Automata," colloquium presented at Indiana University-Purdue University, Indianapolis, April, 1994.

"Dynamic Behavior of Coupled Quantum Dot Cells," P. Douglas Tougaw and Craig S. Lent, presented at the *3rd International Workshop on Computational Electronics*, Portland, OR, May 1994.

Transmission Resonances and Zeros in Quantum Waveguides with Resonantly-Coupled Cavities

Investigators: Wolfgang Porod and Craig S. Lent

We have studied transmission phenomena when coupling a quantum waveguide to a resonant cavity. In particular, we have investigated the properties of the transmission amplitude in the complex-energy plane. We find that, similar to double-barrier resonant tunneling, there are transmission poles in the complex-energy plane for quantum waveguide structures which contain quasi-bound states in attached t-stub resonators. In contrast to double-barrier resonant tunneling, however, we also find that the quantum wire networks also possess transmission zeros (antiresonances), which always occur on the real-energy axis. The existence of transmission zeros is a characteristic feature of quantum waveguide systems with attached resonators, but is absent for double-barrier resonant tunneling, which contains the resonant cavity as part of the transmission channel. We demonstrate that each quasi-bound state of the resonantly-coupled quantum waveguide system leads to a zero-pole pair of the transmission amplitude in the complex-energy plane.

The previously noted resonance - antiresonance behavior of the transmission probability, which leads to its sharp variation as a function of energy, can be understood in terms of these zero-pole pairs. We have also investigated the line shape of the transmission probability in quantum waveguides with resonantly-coupled cavities. Resonance/ antiresonance features in the vicinity of each quasi-bound state can be characterized by a zero-pole pair in the complex-energy plane, which leads to asymmetrical transmission peaks. We have found a generalization of the familiar symmetrical Lorentzian line. Using several examples, we have demonstrated the utility of our proposed line shape to extract the lifetime of the quasi-bound state by a fit to the data. We also discussed the asymmetrical line shapes in the context of Fano resonances. This work has lead to extensive discussions with several groups actively involved in the theory and fabrication of resonant tunneling structures, especially Luscombe and Randall at Texas Instruments, Frensley at the University of Texas at Dallas, and Ting in McGill's group at the California Institute of Technology.

Resulting Publications and Presentations:

Wolfgang Porod, Zhi-an Shao, and Craig S. Lent, "Transmission Resonances and Zeros in Quantum Waveguides with Resonantly-Coupled Cavities," *Applied Physics Letters* **61**, 1350 - 1352 (1992).

Wolfgang Porod, Zhi-an Shao, and Craig S. Lent, "Transmission Resonances and Zeros in Quantum Waveguides with Resonantly-Coupled Cavities," seminar at the Beckman Institute, University of Illinois, Urbana, Illinois, April 1992.

Zhi-an Shao, Wolfgang Porod, and Craig S. Lent, "A Numerical Study of Transmission Resonances and Zeros in Quantum Waveguide Structures," *Proceedings of the International Workshop on Computational Electronics*, pp. 253 -256; presented at *the International Workshop on Computational Electronics*, Urbana, Illinois, May 1992.

Wolfgang Porod, Zhi-an Shao, and Craig S. Lent, "Resonance-Antiresonance Line Shape for Transmission in Quantum Waveguides with Resonantly-Coupled Cavities," *Phys. Rev. B* **48**, 8495 - 8498 (1993)

Zhi-an Shao, Wolfgang Porod, and Craig S. Lent, "Transmission Resonances and Zeros in Quantum Waveguide Systems with Attached Resonators," *Phys. Rev. B* **49** (1 March 1994).

Zhi-an Shao, Wolfgang Porod, and Craig S. Lent, "A Numerical Study of Transmission Resonances and Zeros in Quantum Waveguide Structures," *Proceedings of the International Workshop on Computational Electronics*, pp. 253 - 256; presented at the *International Workshop on Computational Electronics*, Urbana, Illinois, May 1992.

Zhi-an Shao, Wolfgang Porod, and Craig S. Lent, "Resonance/Antiresonance Lineshape for Transmission in Quantum Waveguides with Resonantly-Coupled Cavities," in *Proceedings of the International Workshop on Computational Electronics*, C. Snowden and M. Howes, eds., pp. 328 - 332; presented at the *International Workshop on Computational Electronics*, Leeds, England, August 1993.

Zhi-an Shao, Craig S. Lent, and Wolfgang Porod, "Resonance-Antiresonance Features for Transmission in Quantum Waveguide Systems," abstract published in the *Bulletin of the APS*, Vol. 39, No. 1, p. 745, March 1994; presented at the *1994 March Meeting of the American Physical Society*, Pittsburgh, Pennsylvania, March 1994.

Zhi-an Shao, Wolfgang Porod, and Craig S. Lent, "A Linear Eigenvalue Method for Calculating the Positions of Transmission Poles and Zeros in Resonator Structures," Poster presented at the *Third International Workshop on Computational Electronics*, Portland, Oregon, May 1994.

Minhan Chen and Wolfgang Porod, "Numerical Simulation of the Effect of Surface Charges on Electron Confinement in Quantum Dot Structures," Poster presented at the *Third International Workshop on Computational Electronics*, Portland, Oregon, May 1994.

Design of Quantum Wires at Corrugated Heterointerfaces

Investigators: Wolfgang Porod

We have investigated the formation of a quantum wire structure by the confinement of electrons between lateral quasi-two-dimensional p-n junctions at corrugated GaAs/AlGaAs heterostructures. Such a quantum wire may be realized at the tip of a Si-doped AlGaAs overgrown V groove in a SI-GaAs substrate due to the surface orientation dependence of Si doping. The two-dimensional conduction and valence band profiles for the electron and hole charge densities are obtained numerically within a semiclassical Thomas-Fermi screening model. The quantized electronic wire states at the heterointerface are then obtained by solving the two-dimensional effective mass Schrödinger equation using the calculated potential profile. We have explored the parameter space of the one-dimensional electronic system and we established which features of the structure are dominant factors in controlling the quantum confinement. Specifically, we found that the energy level spacing of the quantum wire depends primarily upon the lateral confinement width in the n-type region at the tip of the V groove. The ground state energy of the wire is shown to depend on both the lateral confinement width and the vertical heterointerface confinement width. We have also studied the effect of lateral gates on the side walls of the V groove in order to obtain direct control of the quantum wire transport properties. Our studies have resulted in an experimental effort in the group of Dr. Jim Merz at UC Santa Barbara, which is aimed at realizing such a quantum wire structure by MBE techniques. Experiments so far have demonstrated the growth capability on corrugated surfaces.

Resulting Publications and Presentations:

Henry K. Harbury, Wolfgang Porod, and Stephen M. Goodnick, "Lateral p-n junctions between quasi two-dimensional electron and hole systems at corrugated GaAs/AlGaAs interfaces," *J. of Vac. Sci. and Technol. B* **10**, 2051 - 2055 (1992).

Wolfgang Porod, Henry K. Harbury, and Stephen M. Goodnick, "Lateral p-n junctions and quantum wires formed by quasi two-dimensional electron and hole systems at corrugated GaAs/AlGaAs interfaces," *Appl. Phys. Lett.* **61**, 1823 - 1825 (1992).

Henry K. Harbury, Wolfgang Porod, and Stephen M. Goodnick, "A Novel Quantum Wire Formed by Lateral p-n-p Junctions Between Quasi-Two-Dimensional Electron and Hole Systems at Corrugated GaAs/AlGaAs Interfaces," *J. Appl. Phys.* **73**, 1509 - 1520 (1993).

Henry K. Harbury, Wolfgang Porod, and Stephen M. Goodnick, "A Numerical Study of Lateral p-n Junctions between Quasi Two-Dimensional Electron and Hole Systems at Corrugated GaAs/AlGaAs Interfaces," *Proceedings of the International Workshop on Computational Electronics*, pp. 249 -- 251; presented at the *International Workshop on Computational Electronics*, Urbana, Illinois, May 1992.

Henry K. Harbury, Wolfgang Porod, and Stephen M. Goodnick, "Novel Quantum Wire Formed by Lateral p-n-p Junctions Between Quasi-Two-Dimensional Electron and Hole Systems at Corrugated GaAs/AlGaAs Interfaces," presented at the *International Workshop on Quantum Structures*, Santa Barbara, California, March 1993.

Quantum Scattering States in Open Two-Dimensional Systems

Investigators: Wolfgang Porod

We have developed a method to solve the two-dimensional effective-mass Schrödinger equation for scattering states on open boundary domains. The boundary conditions are developed by partial wave expansion of the known far-field solution, in the spirit of the QTBM, and by enforcing continuity of the complex wavefunction and its derivative across the domain periphery. The problem is formulated within the finite element method and the algorithm is used to solve for the scattering states of a two-dimensional electron gas with point scatterers. This technique may be used to study the local field effects within the vicinity of scattering defects in mesoscopic structures. Dr. Kent Smith, who is a Distinguished Member of Technical Staff at AT&T Bell Laboratories at Murray Hill, recently visited our group to discuss applying our boundary conditions to open two-dimensional problems for his semiconductor laser simulations.

Resulting Publications and Presentations:

Henry K. Harbury and Wolfgang Porod, "Numerical Method to Obtain the Two-Dimensional Electronic States for Open Boundary Scattering Problems," pp. 323, Proceedings of the *International Workshop on Computational Electronics*, Leeds, England, August 1993.

Henry K. Harbury and Wolfgang Porod, "Numerical Linear Response Study of the Electron Wind Force of Electromigration in Quasi-1D Transport," in *Proceedings of the International Workshop on Computational Electronics*, C. Snowden and M. Howes, eds., pp. 323 - 327; presented at the *International Workshop on Computational Electronics*, Leeds, England, August 1993.

Henry K. Harbury and Wolfgang Porod, "Local Fields in Open Two-Dimensional Electronic Scattering Systems," abstract published in the *Bulletin of the APS*, Vol. 39, No. 1, p. 75, March 1994; presented at the *1994 March Meeting of the American Physical Society*, Pittsburgh, Pennsylvania, March 1994.

Henry K. Harbury, Wolfgang Porod, and R. Kent Smith, "Open Boundary Conditions for Multidimensional Electronic Scattering States," presented at the *Third International Workshop on Computational Electronics*, Portland, Oregon, May 1994.

Carrier Dynamics in Quantum Wires

Investigators: Wolfgang Porod

Using the Monte Carlo technique, we have investigated the thermalization of carriers following a laser pulse excitation. Realistic quantum wire structures are investigated with multiple electronic subbands (on the order of 20). Our simulations include standard polar-optical phonon rates, and an improved technique to account for carrier-carrier scattering. We find that the reduced phase space in these quasi-one-dimensional systems leads to reduced carrier cooling when compared to bulk samples. These findings are in agreement with recent experiments.

Resulting Publications and Presentations:

L. Rota, F. Rossi, S. M. Goodnick, P. Lugli, E. Molinari, and W. Porod, "Reduced carrier cooling and thermalization in semiconductor quantum wires," *Physical Review B* **47**, 1632 -- 1635 (1993).

L. Rota, F. Rossi, P. Lugli, E. Molinari, S. M. Goodnick, and W. Porod, "Monte Carlo Simulation of a `True' Quantum Wire," presented at the 1992 *Symposium on Compound Semiconductor Physics and Devices*, of SPIE -- The International Society of Optical Engineering, Somerset, New Jersey, March 1992.

Local Field Effects and Electromigration in Mesoscopic Structures

Investigators: Wolfgang Porod and Craig S. Lent

In this ongoing effort, we study the effect of space charges on the current - voltage characteristics of two-dimensional mesoscopic structures. In particular, we focus on the microscopic potential and current variations in the vicinity of scattering centers. The resulting non-uniform carrier distribution gives rise to local-field effects and the so-called residual resistivity dipole. These phenomena are thought to be responsible for the driving force in electromigration, and we believe that the study of such mesoscopic systems may shed light on this important effect.

The (non-uniform) electronic density along the channel influences the electronic wavefunctions through its space charge potential. The Schrödinger and Poisson equations are solved self-consistently within the Hartree approximation. Like in our past studies, the finite element method is used for the discretization of the Schrödinger and Poisson

equations. The Hartree term is obtained by numerically integrating the contributions from the electronic charge density along the channel. An iterative procedure is then employed until self consistency in the wavefunctions and in the space charge potential is achieved.

Resulting Publications and Presentations:

Henry K. Harbury, Wolfgang Porod, and Craig S. Lent, "Field Effects in Self-consistent Transport Calculations for Narrow Split-gate Structures," *Superlattices and Microstructures* **11**, 189 - 193 (1992).

Proximity Effects

Investigators: Gary H. Bernstein

Our basic tool is electron beam lithography of poly (methyl methacrylate) (PMMA). The two central issues to creating very dense patterns are proximity effects and the strength of PMMA "walls". Proximity effects are important since lines are so closely spaced that electron scattering phenomena enter a new regime not commonly studied for the fabrication of conventional integrated circuits. Usually not considered are the high energy secondary electrons of intermediate range. We performed a careful study fitting curves to include a third Gaussian component due to the fast secondary electrons. It was found that the use of the third, intermediate range, component gave a much better fit to the data than the use of only two Gaussian components. We believe this is the only study to date of the proximity effect on the size scales of a few tens of nm.

Resulting Publications and Presentations:

X. Huang, G. H. Bernstein, G. Bazan, and D. A. Hill, "Spatial Density of Lines in PMMA by Electron Beam Lithography," *J. of Vac. Sci. and Technol. A* **11**, 1739-1744 (1993).

Properties of PMMA for Ultra-Dense Patterns.

Investigators: Gary H. Bernstein

The strength of PMMA walls is important because the spacing of the lines is much smaller than the thickness of the starting resist. When the (positive) resist is developed out to form the lines by lift-off, a wall of PMMA remains to form the space between the two lines. Since the length of the walls is very long (on the order of 50 to 100 microns), the walls have a tendency to wave and buckle under the stress of the development process. We found that the lack of stability was due not to process control or technique, but rather to the very slight swelling of the PMMA with the developer leading to buckling of the walls. Furthermore, grating structures had a tendency to fail in very regular arrays of waves which seemed at first to be due to either noise on the electron beam or poor development/ drying procedures. Our study revealed that the regular patterns were in fact due to attractive forces through the developer fluid which set up a pattern of wall failure across the grating.

Resulting Publications and Presentations:

X. Huang, G. Bazan, G. H. Bernstein, and D. A. Hill, "Stability of Thin Resist Walls," *Journal of the Electrochemical Society* **139**, 2952-2956 (1992).

D. A. Hill, X. Huang, G. Bazan, and G. H. Bernstein, "Swelling and Surface Forces-Induced Instabilities in Nanoscopic Polymeric Structures," *J. of Appl. Phys.* **72**, 4088-4094 (1992).

Fabrication of Dense Dot Arrays

Investigators: Gary H. Bernstein

The simplest conception of an array of dots is to directly fabricate metal dots on the surface of a 2DEG formed by a heterostructure. This could be utilized if it is followed by connecting to a top gate after planarization by polyimide, or by reactive ion etching into the doping layer, followed by evaporation of a blanket metal layer, effecting depletion of the etched region and leaving dots in the 2DEG. We have made dot arrays as a test of our lithographic system with dot sizes approaching 10 nm on a 37 nm pitch. These dots, however, are not planned as the first effort in actual dot arrays for nanostructures. A more useful "dot" system is that created by single electron tunneling through small tunnel junctions onto a small metal island. We have demonstrated the processing technique of shadow evaporation with thin Al_2O_3 tunnel barriers, as described in our paper in the *Review of Scientific Instruments*. This technique has recently been refined to decrease the stray capacitance. We have improved our layer-to-layer overlay alignment accuracy considerably. Using our new technique, described in the *Journal of Vacuum Science and Technology A*, we have achieved alignment accuracies beyond the visible limits of our newest field emission scanning electron microscope, with a resolution of about 1.5 nm.

Resulting Publications and Presentations:

S. J. Koester, G. Bazan, G. H. Bernstein, and W. Porod, "Fabrication of Ultrasmall Tunnel Junctions by Electron Beam Lithography, *Rev. of Sci. Instr.* **63**, 1918 - 1921 (1992).

G. Bazan and G. H. Bernstein, "Electron Beam Lithography Over Very Large Scan Fields," *J. Vac. Sci. and Technol. A* **11**, 1745-1752 (1993).

A New Technique for Fabricating Mesoscopic Structures in Silicon

Investigators: Gary H. Bernstein and Wolfgang Porod

In the interest of fabricating wires with new properties and in new materials, we have investigated a novel technique for fabricating mesoscopic structures in general, and quantum wires in particular, in silicon. Initially, we performed a series of experiments to investigate the spatial stability of positive charge induced in SiO_2 by exposure to a beam of electrons. The positive charge caused a shift in the threshold voltage of MOSFET's by up to -15 volts, so that the area exposed to the beam inverted, creating a 2DEG in the

silicon, at a much more negative voltage than did the area left unexposed. We showed through the use of capacitance-voltage measurements, as discussed in our paper in *Scanning*, that the induced positive charge did not appear to move in a measurable way during the testing period. We surmised that by intentionally introducing positive charges into the oxide of a MOSFET in a controlled manner using electron beam lithography techniques, that quantum structures could be fabricated. We have so far investigated various aspects of producing 1D structures with this technique. MOSFET's were exposed by the electron beam in a single line from source to drain. Among the unexposed devices, the Notre Dame devices and commercially fabricated devices showed no structure whatsoever around the threshold voltages. All of the exposed devices showed complicated structure very close to threshold. Steps in the drain conductance against gate voltage indicate that right at threshold, the line does not invert uniformly, leaving a pinched area or areas in series with the resistance of the channel. The steps do not appear in units of $e^2/4h$, as they ought to for point contacts in silicon. We concluded that the lack of predictable step size in the conductance was due to the large series resistance of the 1D channel.

Resulting Publications and Presentations:

G. H. Bernstein, S. W. Polchlopek, R. Kamath, and W. Porod, "Determination of Fixed Electron-Beam-Induced Positive Oxide Charge," *Scanning* **14**, 345 - 349 (1992).

A Rigorous Quantum Transport Formalism to Model Electron Magnetotransport in the Presence of Elastic Scattering

Investigators: Supriyo Bandyopadhyay

A technique to simulate electron magnetotransport in one- and two-dimensional semiconductor mesoscopic structures in the presence of elastic scattering has been developed. This technique yields the spatial distribution of current, carriers, chemical and electrostatic potential, and electric fields within a mesoscopic structure under arbitrary magnetic fields.

Using this technique, we investigated for the first time the influence of evanescent states on quantum transport in mesoscopic systems. These states have a profound influence on transport even though they themselves do not carry current. We studied their effect on conductance quantization, "universal conductance fluctuations," Anderson localization, etc. We found that they are especially important in majority carrier transport when the elastic scatterers are attractive. Evanescent states contribute to the formation of bound donor-like states around attractive elastic scatterers which causes conductance nulls at certain Fermi energies.

Other important results that were found are the following: (a) the spatial distributions of current and carrier concentration in a disordered mesoscopic structure show dramatic differences depending on whether the elastic scatterers are attractive or repulsive, (b) attractive scatterers produce strong current vortices (which are not necessarily centered around the scatterers) whereas repulsive scatterers produce much weaker vortices. These vortices are formed owing to quantum mechanical interference of electrons reflected from the scatterers, (c) edge states form at high magnetic fields with near perfect transmittivity, (d) equipotential surfaces are created along the edges of a mesoscopic structure at high

magnetic fields signalling the onset of the integer quantum Hall effect (this is the first microscopic calculation of the spatial distribution of electrochemical potential) in a structure in the quantum Hall effect regime), (e) magnetic bound states form at certain magnetic fields and destroy the quantum Hall effect in narrow wires, (f) a magnetic field recovers conductance quantization in a disordered structure, (g) the sign of the magnetoresistance of a mesoscopic structure may depend on the impurity configuration, etc.

Resulting Publications and Presentations:

S. Bandyopadhyay, M. Cahay, D. Berman and B. Nayfeh, "The Role of Evanescent States in Quantum Transport Through Disordered Mesoscopic Structures," *Superlattices and Microstructures* **10**, 327 - 332 (1991).

S. Bhobe, W. Porod and S. Bandyopadhyay, ``Analysis and Simulation of velocity Modulation by Selective Doping," *Phys. Stat. Solidi.*, **125**, 375 - 386 (1991).

S. Chaudhuri and S. Bandyopadhyay, ``Spatial Distribution of the Current and Fermi Carriers Around Localized Elastic Scatterers in Quantum Transport" *Phys. Rev. B*, **45**, 11126 - 11135 (1992).

S. Chaudhuri and S. Bandyopadhyay, ``Numerical Calculation of Hybrid Magnetoelectric States in an Electron Waveguide," *J. Appl. Phys.*, **71**, 3027 - 3029 (1992).

S. Chaudhuri and S. Bandyopadhyay, ``Quantum Transport in a Disordered Quantum Wire in the Presence of a Magnetic Field," *Superlattices and Microstructures*, **11**, 241 - 244 (1992).

S. Chaudhuri and S. Bandyopadhyay, ``Diffusive Quantum Transport in the Presence of a Magnetic Field," presented at the International Symposium on Nanostructures and Mesoscopic Systems, Santa Fe, New Mexico, 1991.

M. Cahay, T. Singh and S. Bandyopadhyay, ``Electron emission from a quantum well as a result of exchange and Coulomb interactions," Proceedings of the International Conference on Computational Electronics, 147 - 150, (1992).

S. Bandyopadhyay, B. Das, M. Cahay and S. Chaudhuri, ``Low Temperature Conduction in Ultranarrow Wires: Quantum Transport and Weak Electromigration Causing 1/f Noise," presented at the 183d. Meeting of the Electrochemical Society, Honolulu, Hawaii, May 17, 1993.

S. Bandyopadhyay, "Magnetoresistance Due to Non-Markovian Elastic Scattering" Processes at Low Temperatures, presented at the Granular Nanoelectronics Workshop, Urbana, Illinois, May 1991

S. Bandyopadhyay and M. Cahay, ``Mode Quenching and Space Charge Effects in Mesoscopic Systems," presented at the Spring Meeting of the American Physical Society, Cincinnati, March 1991 (also in Bull. Amer. Phys. Soc., 36, 359 (1991)).

S. Chaudhuri, S. Bandyopadhyay and M. Cahay, ``Spatial distribution of current and the Fermi density of states around impurities in phase coherent transport," presented at the Spring Meeting of the American Physical Society, Indianapolis, March (1992).

S. Bandyopadhyay, S. Chaudhuri and M. Cahay, ``Two dimensional current and probability density profiles in mesoscopic systems in the presence of a magnetic field," presented at the Spring Meeting of the American Physical Society, Indianapolis, March (1992).

S. Chaudhuri, S. Bandyopadhyay and M. Cahay, ``Study of universal conductance fluctuations and quenching of Anderson localization in a magnetic field: a Weber function analysis," presented at the Spring Meeting of the American Physical Society, Indianapolis, March (1992).

S. Chaudhuri, S. Bandyopadhyay and M. Cahay, ``Numerical study of quantum magnetotransport in disordered non-adiabatic constrictions," Proceedings of the International Conference on Computational Electronics, 305 - 308, (1992).

Weak Electromigration in the Phase Coherent Regime in Mesoscopic Structures

Investigators: Supriyo Bandyopadhyay

We studied weak electromigration forces acting on an impurity in a mesoscopic structure which may cause slight impurity motion and give rise to 1/f noise. We calculated the wind force and direct force on an impurity as well as the residual resistivity dipoles that influence the wind force. We found that a magnetic field can either quench or accentuate the electromigration forces and influence its orientation in a significant way.

Resulting Publications and Presentations:

S. Chaudhuri, S. Bandyopadhyay, and M. Cahay, ``Spatial distribution of the current, Fermi carrier density, potential and electric field in a disordered quantum wire in a magnetic field" *Phys. Rev. B* **47**, 12649 (1993).

S. Bandyopadhyay, S. Chaudhuri, B. Das and M. Cahay, ``Features of quantum magnetotransport and electromigration in mesoscopic systems" *Superlattices and Microstructures*, **12**, 123 - 132 (1992).

S. Bandyopadhyay, S. Chaudhuri, B. Das and M. Cahay, ``Magnetotransport and electromigration in mesoscopic systems," Sixth International Conference on Superlattices and Microstructures, Xian, People's Republic of China, August 1992.

N. Telang and S. Bandyopadhyay, ``Influence of Phonons on Electromigration in Ultranarrow Wires," presented at the 183d. Meeting of the Electrochemical Society, Honolulu, Hawaii, May 17, 1993.

Quantum Devices

Investigators: Supriyo Bandyopadhyay

We studied generic quantum interference devices such as T-structure transistors and their properties. As expected, we found that the device characteristics of such elements are very sensitive to slight structural variations indicating that they have little, if any, fabrication

tolerance. We also proposed that such structures may be more suitable as an electro-optic switch and will be very fast and consume very little power.

Resulting Publications and Presentations:

M. Cahay and S. Bandyopadhyay, ``Quantum Interference Devices: The Twilight Zone for ULSI," *IEEE Potentials*, Vol. 12, February Issue, 1993, pp. 18 -23 (INVITED).

Spontaneous spin polarization in an array of quantum dots.

Investigators: Supriyo Bandyopadhyay

We found that an array of quantum dots each hosting a single electron undergoes spontaneous spin polarization to mimic antiferromagnetism. Such a system can be engineered to realize either cellular automata type of computing architecture or random wired logic. The spin polarization can be utilized to encode binary bits. The advantage of using spin is that it is intrinsically bistable in a quantum system, it is immune to electrical noise, switching does not involve physical movement of carriers (simply a spin needs to be toggled to switch a bit) and the antiferromagnetic ordering is preserved even at room temperature. We have designed both combinational (such as half-adders) and sequential memory circuits (such as S-R flip-flops) using this scheme. It may also be possible to configure cellular automata rules and drive the architecture using a coherent electromagnetic field used as a clock. The induces spin flip via magnetic dipole transitions. This scheme can approach dissipationless computation.

Resulting Publications and Presentations:

S. Bandyopadhyay, B. Das and A. E. Miller, ``Supercomputing with Spin Polarized Single Electrons in a Quantum Coupled Architecture," *Nanotechnology* (in press).

Bandyopadhyay, A. E. Miller and B. Das, ``Spontaneous Spin Polarization in a Two Dimensional Array of Quantum Dots: Possibilities for Novel Quantum Coupled Cellular Automata Computing Architectures," presented at the 185th Meeting of the Electrochemical Society, San Francisco, May 22, 1994.

S. Bandyopadhyay, "Single Electronics with Nanophase Materials", presented at Argonne National Laboratory, Argonne, Illinois, June 1992

S. Bandyopadhyay, "Supercomputing with spin polarized single electrons", presented at School of Electrical Engineering, Purdue University, March 1993.

S. Bandyopadhyay, Non-linear Optics with Nanophase Materials, invited presented at the International Workshop on Nanophase Materials, Davos, Switzerland, March 15, 1994.

Hot electron transport in a quantum wire in the presence of a magnetic field

Investigators: Supriyo Bandyopadhyay

We have studied hot electron transport in quantum wires in the presence of an arbitrary magnetic field. This is the first investigation of this regime in hot electron transport. We found several interesting results: (a) acoustic phonon scattering in a quantum wire can be dramatically quenched by a magnetic field (by up to six orders of magnitude at a field of 10 tesla). This quenching is important in understanding the suppression of inelastic backscattering between edge states at high magnetic fields which is the central ingredient of the Büttiker picture of the quantum Hall effect. Such quenching can cause strong negative magnetoresistance in quantum wires. Additionally, the scattering rates differ by many orders of magnitude at electron energies just below and just above a subband minimum. This may result in negative differential resistance in a quantum wire at very low electric fields via the Riddoch-Ridley mechanism. (b). We also found that confined optical and surface phonon scattering in quantum wires is increased by a magnetic field which destroys the orthogonality between phonon modes and electronic states of opposite parity. (c) We found that in quantum wires, the ensemble average transport lifetime of electrons can be negative. This is a peculiarity of one-dimensional structures and is never observed in bulk or two-dimensional structures. This can give rise to very low field velocity overshoot. (d) Finally, we found that a magnetic field can increase the electron mobility in a quantum wire by a factor of two at a field of 10 tesla.

Resulting Publications and Presentations:

N. Telang and S. Bandyopadhyay, ``A Monte Carlo Study of Correlations Between Impurity Scattering Events in a Two dimensional Electron Gas Causing Inhomogeneous Magnetoresistance, *Superlattices and Microstructures* **11**, 99 - 102 (1992).

N. Telang and S. Bandyopadhyay, ``The effect of collision retardation on hot electron transport in a quantum well," *Phys. Rev. B* **47**, 9900 (1993).

N. Telang and S. Bandyopadhyay, ``Quenching of Acoustic Phonon Scattering of Electrons in Semiconductor Quantum Wires Induced by a Magnetic Field" *Appl. Phys. Lett.* **62**, 3161 (1993).

N. Telang and S. Bandyopadhyay, ``The Effect of a Magnetic Field on Polar Optical and Surface Phonon Scattering Rates," *Phys. Rev. B*, **48**, 18002 (1993).

N. Telang and S. Bandyopadhyay, ``Modulation of Electron Phonon Scattering in Quantum Wires by a Magnetic Field," *Semicon. Sci. Technol.* **9**, 955 (1994).

N. Telang and S. Bandyopadhyay, ``A Monte Carlo study of correlations between impurity scattering events giving rise to anomalous magnetoresistance in a 2 DEG," presented at the Spring Meeting of the American Physical Society, Indianapolis, March (1992).

The Effects of a Magnetic Field on Phonon Scattering in Quasi One Dimensional Systems

Investigators: Supriyo Bandyopadhyay

We have rigorously calculated electron-phonon scattering rates in quasi one dimensional systems in the presence of an external magnetic field. We have found that a magnetic field dramatically reduces both polar and non-polar acoustic phonon scattering by orders of magnitude which has important implications for the quantum Hall effect. The reduction is caused by a decrease in the overlap between initial and final state electron wavefunctions. The scattering rates due to longitudinal polar and non-polar optical phonons and surface phonons increases in a magnetic field (though the change is not as dramatic as in the case of acoustic phonons). This is attributed to the opening of many new scattering channels associated with the breaking of orthogonality between electron wavefunctions and confined phonon modes in the presence of a magnetic field.

Resulting Publications and Presentations:

N. Telang and S. Bandyopadhyay, ``Quenching of Acoustic Phonon Scattering of Electrons in Semiconductor Quantum Wires Induced by a Magnetic Field," *Appl. Phys. Lett.* (*in press*).

N. Telang and S. Bandyopadhyay, ``Electron phonon scattering in quantum wires subjected to high magnetic field", *Proceedings of the International Conference on Computational Electronics*, 237 - 240, (1992).

N. Telang and S. Bandyopadhyay, ``The Effects of a Magnetic Field on Electron Phonon Scattering in Quantum Wires by a Magnetic Field", submitted to *Phys. Rev. B.*

Supercomputing with Spin Polarized Single Electrons

Investigators: Supriyo Bandyopadhyay

We have proposed a novel quantum technology for ultra-fast, ultra-dense and ultra-low power supercomputing. The technology utilizes single electrons as binary logic devices in which the *spin* of the electron encodes the bit information. The architecture mimics two dimensional cellular automata. It is realized by laying out on a wafer regimented arrays of nanophase particles each hosting an electron. Various types of logic gates, combinational circuits for arithmetic logic units, and sequential circuits for memory can be realized.

The technology has many advantages such as (1) the absence of physical interconnects between devices (inter-device interaction is provided by quantum mechanical coupling between adjacent electrons), (2) ultrafast switching times of 1 picosecond for individual devices, (3) extremely high bit density approaching 10 Terabits/sq-cm, (4) non-volatile memory, (5) robustness and possible *room temperature* operation with very high noise margin and reliability, (6) a very low power delay product for switching a single bit 10^{-20} Joules), and (7) a very small power dissipation of a few tens of nanowatts per bit. We have also proposed a new non-lithographic fabrication technology for realizing these chips.

Resulting Publications and Presentations:

S. Bandyopadhyay, B. Das and A.E. Miller, "Supercomputing with Spin Polarized Single Electrons in a Quantum-coupled Architecture," submitted to *J. Appl. Physics*.

S. Bandyopadhyay, "Single Electronics with Nanophase Materials", invited lecture presented at Argonne National Laboratory, Argonne, Illinois, June 1992.

S. Bandyopadhyay, "Supercomputing with spin polarized single electrons", invited seminar presented at School of Electrical Engineering, Purdue University, March 1993.

Single Particle Lifetimes in Quasi-one-dimensional Structures

Investigators: Supriyo Bandyopadhyay

We have experimentally measured, for the first time, the relaxation time for single particle excitations in quantum wires as a function of both wire width and carrier concentration. The measurements were made in a back-gated AlGaAs/GaAs heterostructure at 4.2 K. The experimental data show excellent agreement with a theoretical model which uses only one fitting parameter (to account for screening).

Resulting Publications and Presentations:

M. Cahay, T. Singh and S. Bandyopadhyay, ``Electron emission from a quantum well as a result of exchange and Coulomb interactions", Proceedings of the International Conference on Computational Electronics, 147 - 150, (1992).

Photovoltaic Effect

Investigators: Gary H. Bernstein

Of current scientific interest, the existence of DC photovoltages induced by bombardment of microwave radiation, i.e. the photovoltaic (PV) effect, has proved fertile ground for studying the interaction of high frequency electric fields on conduction electrons in metals. One present model for the PV effect is that electrons absorb microwave photons, and being out of equilibrium with the Fermi sea, the energetic electrons diffuse in a direction preferential to the precise impurity distribution. Because of this, a DC voltage on the order of nV develops across the leads of the device.

We have been involved in a collaboration with Dr. N. Giordano and graduate student R. Bartolo at Purdue University to study the photovoltaic effect in mesoscopic structures. Prior to our involvement, their work was confined to structures with dimensions of about one μm. We have collaborated to produce a variety of structures with dimensions to 50 nm in the form of wires and rings of diameter 330 to 500 nm, measured at Purdue University.

We have fabricated (on glass substrates) gold 1-D wires with widths of 50 to 70 nm, thicknesses of 20 nm, and total lengths of up to 1.5 μm. These structures clearly showed evidence of the PV effect at 4.2 K. Although the results from the small wires were

essentially the same as that of the larger structures, the small structures allowed comparisons with similarly sized lines formed in the shape of rings for investigation of the Aharonov-Bohm (A-B) effect. In these structures, A-B oscillations in the PV data were clearly visible. The Fourier transform in magnetic field yields a clear peak at precisely the correct location corresponding to h/e oscillations.

Previous observations of the A-B effect have been performed at temperatures of less than 0.1 K. Here the direct observation of an A-B related phenomenon at much higher temperatures, to more than 10 K, has been demonstrated. This could prove useful in future investigations of the A-B effect and other physical phenomena.

Resulting Presentations:

R. E. Bartolo, X. Huang, N. Giordano, and G. H. Bernstein, "Observation of Aharonov-Bohm Oscillations in the Mesoscopic Photovoltaic Effect," presented at the *March Meeting of the American Physical Society*, Pittsburgh, Pennsylvania, March 1994.

III. Research Personnel Supported

Craig S. Lent	Assoc. Professor
Wolfgang Porod	Professor
Supriyo Bandyopadhyay	Assoc. Professor
Gary H. Bernstein	Assoc. Professor

IV. Theses Supervised

Renu Kamath, M.S.E.E. August 1992. Thesis title: Breakdown in Thin SiO_2 Films: (advisors: G.H. Bernstein and W. Porod)

S. Chaudhuri, M.S.E.E. May 1992. Thesis title: A study of quantum magnetotransport in disordered mesoscopic structures. (advisor: S. Bandyopadhyay)

S. Subramaniam, Ph.D. May 1993. Thesis title: A study of electron transport in back-gated GaAs/AlGaAs modulation doped heterostructures for novel device applications. (advisor: S. Bandyopadhyay)

Brad Campbell, M.S.E.E. January 1993. Thesis title: Nanofabricated Quantum Structures in Silicon Inversion Layers. (advisor: G.H. Bernstein)

Greg Bazan, M.S.E.E. May 1991. Thesis title: Ultra-short Gate GaAs MESFET's Fabricated by Electron Beam Lithography. (advisor: G.H. Bernstein)

Steve Koester, M.S.E.E. May 1991. Thesis title: Single Electron Tunneling in a Uniform Array of Quantum Dots. (advisor: G.H. Bernstein)

N. Telang, M.S.E.E. December 1991 Thesis title: Monte Carlo simulation of hot electron transport in two-dimensional systems. (advisor: S. Bandyopadhyay)

Doug Tougaw, M.S.E.E. December 1993. (advisor: Craig S. Lent)

Manhua Leng, M.S.E.E. December 1992. (advisor: Craig S. Lent)

Manhua Leng Ph.D to be defended Sept. 1994. Thesis title: Quantum Magnetotransport. (advisor: Craig S. Lent)

Henry Harbury Ph.D. to be defended August 1994. Thesis title: Quantum Scattering in Open Two-dimensional Systems. (advisor: Wolfgang Porod)

V. Journal Publications

Craig S. Lent, "Edge States in a Circular Quantum Dot," Phys. Rev. B **43**, 4179 (1991).

Craig S. Lent and Manhua Leng, "Bloch states of electrons in a corrugated quantum channel," *Applied Physics Letters* **58**, 1650 (1991)

Craig S. Lent and Manhua Leng, "Magnetic edge states in a corrugated quantum channel," *Journal of Applied Physics* **70**, 3157 (1991).

Manhua Leng and Craig S. Lent, "Magnetic Edge States in a Quantum Channel with a Periodic Array of Antidots," *Superlattices and Microstructures* **11**, 351 (1992).

Manhua Leng and Craig S. Lent, "Recovery of quantized ballistic conductance in a periodically modulated channel," *Physical Review Letters* **71**, 137 (1993).

Manhua Leng and Craig S. Lent, "The Quantum Transmitting Boundary Method in an Applied Magnetic Field," to appear in *Journal of Applied Physics.*

Manhua Leng and Craig S. Lent "Recovery of quantized ballistic conductance in a periodically modulated channel," submitted to P*hysical Review* B.

Craig S. Lent, "A Simple Model of Coulomb Effects in Semiconductor Nanostructures," in *Nanostructures and Mesoscopic Systems*, edited by Wiley P. Kirk and Mark A. Reed, 183 (Academic Press, Boston, 1992).

Craig S. Lent, P. Douglas Tougaw, and Wolfgang Porod, "Bistable Saturation in Coupled Quantum Dots for Quantum Cellular Automata," *Appl. Phys. Lett.*, **62**, 714 (1993).

Craig S. Lent, P. Douglas Tougaw, Wolfgang Porod and Gary H. Bernstein, "Quantum Cellular Automata," to appear in *Nanotechnology* **4**, (1993).

Craig S. Lent and P. Douglas Tougaw, "Lines of interacting quantum-dot cells: a binary wire," *Journal of Applied Physics*, **74**, 6227 (1993).

Craig S. Lent, P. Douglas Tougaw, and Wolfgang Porod, "Bistable saturation in coupled quantum-dot cells," *Journal of Applied Physics* **74**, 3558 (1993).

Craig S. Lent and P. Douglas Tougaw, "Bistable saturation due to single electron charging in rings of tunnel junctions," *Journal of Applied Physics* **75**, 4077-4080 (1994).

P. Douglas Tougaw and Craig S. Lent, "Logical devices implemented using quantum cellular automata", *Journal of Applied Physics* 75, 1818-1825 (1994).

Wolfgang Porod, Zhi-an Shao, and Craig S. Lent, "Transmission Resonances and Zeros in Quantum Waveguides with Resonantly-Coupled Cavities," *Applied Physics Letters* **61**, 1350 - 1352 (1992).

Wolfgang Porod, Zhi-an Shao, and Craig S. Lent, "Resonance-Antiresonance Line Shape for Transmission in Quantum Waveguides with Resonantly-Coupled Cavities," *Phys. Rev. B* **48**, 8495 - 8498 (1993)

Zhi-an Shao, Wolfgang Porod, and Craig S. Lent, "Transmission Resonances and Zeros in Quantum Waveguide Systems with Attached Resonators," *Phys. Rev. B* **49** (1 March 1994).

Henry K. Harbury, Wolfgang Porod, and Stephen M. Goodnick, "Lateral p-n junctions between quasi two-dimensional electron and hole systems at corrugated GaAs/AlGaAs interfaces," *J. of Vac. Sci. and Technol. B* **10**, 2051 - 2055 (1992).

Wolfgang Porod, Henry K. Harbury, and Stephen M. Goodnick, "Lateral p-n junctions and quantum wires formed by quasi two-dimensional electron and hole systems at corrugated GaAs/AlGaAs interfaces," *Appl. Phys. Lett.* **61**, 1823 - 1825 (1992).

Henry K. Harbury, Wolfgang Porod, and Stephen M. Goodnick, "A Novel Quantum Wire Formed by Lateral p-n-p Junctions Between Quasi-Two-Dimensional Electron and Hole Systems at Corrugated GaAs/AlGaAs Interfaces," *J. Appl. Phys.* **73**, 1509 - 1520 (1993).

L. Rota, F. Rossi, S. M. Goodnick, P. Lugli, E. Molinari, and W. Porod, "Reduced carrier cooling and thermalization in semiconductor quantum wires," *Physical Review B* **47**, 1632 -- 1635 (1993).

Henry K. Harbury, Wolfgang Porod, and Craig S. Lent, "Field Effects in Self-consistent Transport Calculations for Narrow Split-gate Structures," *Superlattices and Microstructures* **11**, 189 - 193 (1992).

X. Huang, G. H. Bernstein, G. Bazan, and D. A. Hill, "Spatial Density of Lines in PMMA by Electron Beam Lithography," *J. of Vac. Sci. and Technol. A* **11**, 1739-1744 (1993).

X. Huang, G. Bazan, G. H. Bernstein, and D. A. Hill, "Stability of Thin Resist Walls," *Journal of the Electrochemical Society* **139**, 2952-2956 (1992).

D. A. Hill, X. Huang, G. Bazan, and G. H. Bernstein, "Swelling and Surface Forces-Induced Instabilities in Nanoscopic Polymeric Structures," *J. of Appl. Phys.* **72**, 4088-4094 (1992).

S. J. Koester, G. Bazan, G. H. Bernstein, and W. Porod, "Fabrication of Ultrasmall Tunnel Junctions by Electron Beam Lithography, *Rev. of Sci. Instr.* **63**, 1918 - 1921 (1992).

G. Bazan and G. H. Bernstein, "Electron Beam Lithography Over Very Large Scan Fields," *J. Vac. Sci. and Technol. A* **11**, 1745-1752 (1993).

G. H. Bernstein, S. W. Polchlopek, R. Kamath, and W. Porod, "Determination of Fixed Electron-Beam-Induced Positive Oxide Charge," *Scanning* **14**, 345 - 349 (1992).

S. Bandyopadhyay, M. Cahay, D. Berman and B. Nayfeh, "The Role of Evanescent States in Quantum Transport Through Disordered Mesoscopic Structures," *Superlattices and Microstructures* **10**, 327 - 332 (1991).

S. Bhobe, W. Porod and S. Bandyopadhyay, ``Analysis and Simulation of velocity Modulation by Selective Doping," *Phys. Stat. Solidi.*, **125**, 375 - 386 (1991).

S. Chaudhuri and S. Bandyopadhyay, ``Spatial Distribution of the Current and Fermi Carriers Around Localized Elastic Scatterers in Quantum Transport" *Phys. Rev. B*, **45**, 11126 - 11135 (1992).

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S. Chaudhuri, S. Bandyopadhyay, and M. Cahay, ``Spatial distribution of the current, Fermi carrier density, potential and electric field in a disordered quantum wire in a magnetic field" *Phys. Rev. B* **47**, 12649 (1993).

S. Bandyopadhyay, S. Chaudhuri, B. Das and M. Cahay, ``Features of quantum magnetotransport and electromigration in mesoscopic systems" *Superlattices and Microstructures*, **12**, 123 - 132 (1992).

M. Cahay and S. Bandyopadhyay, ``Quantum Interference Devices: The Twilight Zone for ULSI," *IEEE Potentials*, Vol. 12, February Issue, 1993, pp. 18 -23 (INVITED).

S. Bandyopadhyay, B. Das and A. E. Miller, ``Supercomputing with Spin Polarized Single Electrons in a Quantum Coupled Architecture," *Nanotechnology* (in press).

N. Telang and S. Bandyopadhyay, ``A Monte Carlo Study of Correlations Between Impurity Scattering Events in a Two dimensional Electron Gas Causing Inhomogeneous Magnetoresistance, *Superlattice and Microstructures* **11**, 99 - 102 (1992).

N. Telang and S. Bandyopadhyay, ``The effect of collision retardation on hot electron transport in a quantum well," *Phys. Rev. B* **47**, 9900 (1993).

N. Telang and S. Bandyopadhyay, ``Quenching of Acoustic Phonon Scattering of Electrons in Semiconductor Quantum Wires Induced by a Magnetic Field" *Appl. Phys. Lett.* **62**, 3161 (1993).

N. Telang and S. Bandyopadhyay, ``The Effect of a Magnetic Field on Polar Optical and Surface Phonon Scattering Rates," *Phys. Rev. B*, **48**, 18002 (1993).

N. Telang and S. Bandyopadhyay, ``Modulation of Electron Phonon Scattering in Quantum Wires by a Magnetic Field," *Semicon. Sci. Technol.* **9**, 955 (1994).

N. Telang and S. Bandyopadhyay, ``Quenching of Acoustic Phonon Scattering of Electrons in Semiconductor Quantum Wires Induced by a Magnetic Field" *Appl. Phys. Lett. (in press).*

S. Bandyopadhyay, B. Das and A.E. Miller, "Supercomputing with Spin Polarized Single Electrons in a Quantum-coupled Architecture," submitted to *J. Appl. Physics*.